RELATIVE POPULATION OF ^{6}Be AND ^{8}Be CLUSTERS IN THE DECAY OF EXCITED COMPOUND NUCLEUS ^{124}Ce* USING THE DYNAMICAL CLUSTER-DECAY MODEL*

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The decay of proton-rich compound nucleus ^{124}Ce*, formed in ^{32}S+^{92}Mo reaction at an above barrier laboratory energy of 150 MeV, is studied within the dynamical cluster-decay model (DCM) with effects of deformations up to hexadecapole and "compact" orientations of nuclei included in it. Treating the experimental data on the statistical code PACE4 shows large deviations in all cases of proton clusters $2p$, $3p$ and $4p$, constituting evaporation residue (ER), and ^{6}Be, the intermediate mass fragment (IMF). Though the data is observed up to ^{10}C, the ^{8}Be decay is not observed in this experiment. Using the DCM, for the best fitted cross-sections of two ERs $(2p, 3p)$ and two IMFs (^{5}Li, ^{6}Be), the relative cross-section of ^{8}Be is found to be bigger than that of ^{6}Be. The only parameter of the model is the neck-length ΔR, related to "barrier lowering" parameter.

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1. Introduction

Recently [1], various decay products of the compound nucleus (CN) ^{124}Ce*, formed in ^{32}S+^{92}Mo reaction, were measured at the above barrier beam energy of 150 MeV, equivalently, the center-of-mass energy $E_{\rm cm}$ = 111.3 MeV (Coulomb barrier $\sim$ 109 MeV). The observed decay products are the heavy residues ^{121}La, $^{120-122}$Ba, $^{118-121}$Cs, $^{117-120}$Xe, ^{117}I, and ^{114}Te, which refer to complementary light particles (LPs) $2p$, $3p$ (or ^{3}H and ^{3}He) and ^{4}Li (or $4p$ and ^{4}He), and the intermediate mass fragments (IMFs) ^{5}Li (or ^{5}Be), ^{6}Be (or ^{6}Li), ^{7}B (or ^{7}Be), and ^{10}C. The relative cross-sections of various decay products are obtained by normalizing them with respect to

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(w.r.t.) that of ^{120}Cs, which itself could be populated only by the evaporation of $3pn$, *i.e.*, ^{4}Li, from the CN. ^{124}Ce being a proton-rich, near the proton-drip line nucleus, ^{122}Ba, ^{121}Cs and ^{120}Xe residues are produced, respectively, due to the evaporation of $2p$, $3p$ and $4p$, and with enhanced cross-sections. The statistical code PACE4 shows large deviations of its predictions from experimental data in all cases of proton clusters ($2p$, $3p$, $4p$) and the ^{118}Xe residue which refers to the ^{6}Be decay. The ^{116}Xe ($\equiv {}^{8}$Be) decay is not observed in this experiment (even the upper limit is not given), and the decay mechanism of ^{118}Xe ($\equiv {}^{6}$Be) is not fully established via the statistical code. In this paper, we explore the decay mechanism of ^{124}Ce* on the basis of the dynamical cluster-decay model (DCM) [2–7].

For the ground-state decay of ^{124}Ce and other neighboring nuclei, studied on the basis of preformed cluster model (PCM) of Gupta *et al.* [8], the calculated preformation probabilities P_0 and decay half-lives $T_{1/2}$ show a clear preference for $A = 4$n, α-nuclei, like ^{8}Be, ^{12}C, *etc.*, emitted from $N = Z$ parents. As the N/Z ratio for parent nuclei becomes larger than one, the $A = 4n + 2$, non-α nuclei clusters, like the ones observed in natural cluster radioactivity, also become prominent, though still with lesser probability than for $A = 4n$ α-nuclei clusters [8]. In this work, we are interested to check the relative production of ^{8}Be w.r.t. ^{6}Be for the decay of hot CN ^{124}Ce* at a fixed CN excitation energy E^{*}. Note that PCM is a $T = 0$ version of DCM, or in fact, DCM is an extended version of PCM for $T \neq 0$ systems.

A brief outline of DCM is given in Section 2. The results of calculation for the decay of ^{124}Ce*, formed in ^{32}S+^{92}Mo reaction at $E_{\rm cm} = 111.3$ MeV, are discussed in Section 3, with a summary and conclusions in Section 4.

2. The dynamical cluster-decay model (DCM)

In DCM, decay of an excited CN is studied as collective cluster emission of LPs, IMFs and fusion–fission (ff), *i.e.*, decay channels of all processes are treated as preformed clusters with relative probabilities, before penetrating the interaction barrier, in contrast to statistical models where each process is treated on a different footing. The structure effects of CN are thus included via the preformation factor, which are not there in statistical fission model.

The decay of hot, rotating CN in DCM is worked out in terms of the decoupled relative separation R and mass asymmetry $\eta\,[= (A_1 - A_2)/(A_1 + A_2)]$ coordinates, defining the CN decay or formation cross-section as

$$\sigma = \sum_{\ell=0}^{\ell_{\max}} \sigma_\ell = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{\max}} (2\ell+1) P_0 P\,; \qquad k = \sqrt{\frac{2\mu E_{\rm cm}}{\hbar^2}}\,. \tag{2.1}$$

Here, P_0 is the preformation probability, referring to η-motion and P, the penetrability, to R-motion. μ is the reduced mass and $\ell_{\max}$ is the maximum angular momentum, defined for LPs evaporation residue (ER) cross-section $\sigma_{\rm ER} \to 0$. P_0 of the fragments are given by the solutions of stationary Schrödinger equation in η at fixed $R = R_a$, defining the first turning point of the penetration path for different ℓ values, as

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta} + V_R(\eta, T)\right\}\psi^\nu(\eta) = E^\nu\psi^\nu(\eta)\,, \tag{2.2}$$

with $\nu = 0, 1, 2, 3\ldots$ referring to ground-state ($\nu = 0$) and excited-states solutions. The mass parameters $B_{\eta\eta}$ in Eq. (2.2) are the smooth classical hydrodynamical masses, used here for simplicity.

For the decay of hot CN, the first turning point R_a of penetration path, used for calculating P, is postulated as

$$R_a(T, \eta, \alpha) = R_t(T, \eta, \alpha) + \Delta R(T)\,, \tag{2.3}$$

where, $R_t = R_1(T, \eta, \alpha_1) + R_2(T, \eta, \alpha_2)$ and ΔR is the neck-length parameter that assimilates the deformation and neck formation effects between two nuclei, introduced within the extended orbiting cluster model of Gupta and collaborators [9], similar to that used in both the scission-point and saddle-point statistical fission models. The corresponding potential $V(R_a, \ell)$ is related to the top of the barrier $V_{\rm B}(\ell)$ for each ℓ value, by defining their difference $\Delta V_{\rm B}(\ell)$ as the effective "barrier lowering"

$$\Delta V_{\rm B}(\ell) = V(R_a, \ell) - V_{\rm B}(\ell)\,. \tag{2.4}$$

Apparently, the fitting parameter ΔR controls the "barrier lowering" $\Delta V_{\rm B}$.

The fragmentation potential, used in Eq. (2.2), is calculated according to the Strutinsky renormalizing procedure ($B = V_{\rm LDM} + \delta U$), as

$$\begin{aligned} V_R(\eta, T) \;=\; & -\sum_{i=1}^{2}\left[V_{\rm LDM}(A_i, Z_i, T)\right] + \sum_{i=1}^{2}\left[\delta U_i\right]\exp\left(-\frac{T^2}{T_0^2}\right) \\ & + V_P\left(R, A_i, \beta_{\lambda i}, \theta_i, T\right) + V_C\left(R, Z_i, \beta_{\lambda i}, \theta_i, T\right) \\ & + V_\ell\left(R, A_i, \beta_{\lambda i}, \theta_i, T\right)\,. \end{aligned} \tag{2.5}$$

Here, $V_{\rm LDM}(T)$ is the liquid drop energy of Davidson *et al.* [10] and the "empirical" shell corrections δU are from [11], taken to go to zero exponentially with T. $T_0 = 1.5$ MeV, which means that the δU reduce nearly to zero for $T > 4$ MeV. V_P, V_C and V_ℓ are for deformed, oriented nuclei.

For R-motion, using the WKB approximation, the penetrability

$$P = \exp\left(-\frac{2}{\hbar}\int_{R_a}^{R_b}\left\{2\mu[V(R, T) - Q_{\rm eff}]\right\}^{1/2} dR\right) \tag{2.6}$$

is solved analytically, with the second turning point R_b satisfying

$$V(R_a) = V(R_b) = Q_{\text{eff}}(T, \ell = 0) = \text{TKE}(T)\,. \quad (2.7)$$

Evidently, $V(R_a)$ acts like an effective Q-value, given by total kinetic energy TKE, and R_a is same for all ℓ values.

3. Calculations and results

Figure 1 shows the calculated fragmentation potential as a function of fragment mass, for the decay of CN ^{124}Ce* at $E_{\text{cm}} = 111.29$ MeV ($E_{\text{Lab}} = 150$ MeV or $T = 2.297$ MeV), illustrated for $\ell_{\text{min}} = 0$ and ℓ_{max} values, using the best fitted ΔR-values for two LPs ($2p$ and $3p$) and two IMFs (^{5}Li and ^{6}Be), whose values are given in figure caption. Note that in Fig. 1, we have replaced the binding energy of the energetically most favored fragment, *i.e.* the fragment having minimum value of binding energy, with the binding energy of the fragment of interest from experiment's point of view. For example, the energetically favored fragment for $A_2 = 2$ is ^{2}H but it is replaced by $2p$ (and complementary heavy fragment). Similarly, ^{3}H, ^{6}Li, ^{7}Li, and ^{10}B are replaced with $3p$, ^{6}Be, ^{7}B and ^{10}C, *etc.*, respectively. We notice in Fig. 1 that ^{8}Be occurs at a deeper minimum compared to ^{6}Be, at both ℓ values, establishing that ^{8}Be decay is preferred over ^{6}Be. Also, we notice from the caption of Fig. 1 that ΔR values are smaller for $2p$ and $3p$ fragments which means that the first turning point radius R_a is smaller for both $2p$ and $3p$

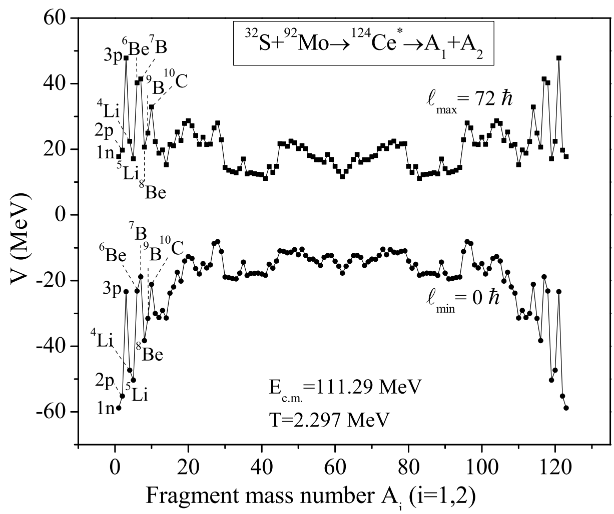

Fig. 1. Mass fragmentation potential for the decay of ^{124}Ce* formed in ^{32}S+^{92}Mo reaction at $E_{\text{cm}} = 111.29$ MeV, plotted for $\ell = 0$ and ℓ_{max}. The best fitted ΔRs are: 1, 0.15, 0.793, 0.575, 0.37 and 1, respectively, for $A_2 = 1$, 2, 3, 4, 5, and 6–62.

fragments, thereby enhancing the Coulomb repulsion for making their decay cross-sections relatively larger, compared to their neighboring fragments. This is more clearly depicted via the calculated preformation probability P_0 plotted in Fig. 2, as a function of light fragment mass number, for two extreme ℓ values. We first notice that the lower ℓ values contribute to LPs and IMFs, and the higher ℓs to heavy mass fragments (HMFs) and near-symmetric and symmetric fission region (nSF and SF, the ff), and in this

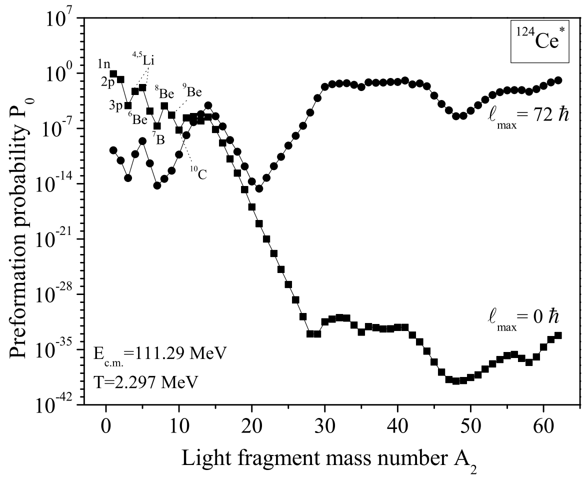

Fig. 2. Preformation probability as a function of fragment mass number for ^{124}Ce* formed in ^{32}S+^{92}Mo reaction at $E_{\rm cm}$ = 111.29 MeV for $\ell_{\rm min}$ and $\ell_{\rm max}$ values.

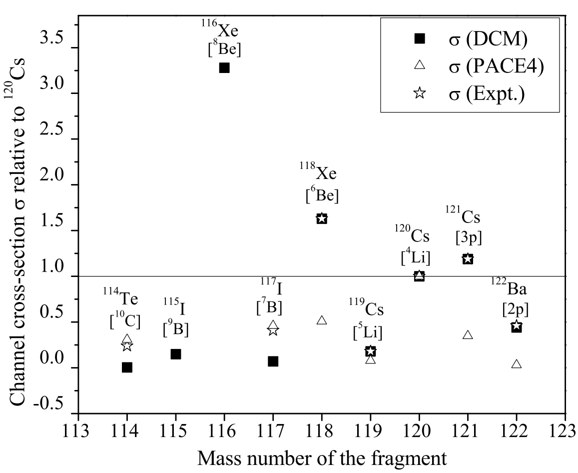

Fig. 3. DCM and PACE4 calculated heavy-residue cross-sections of ^{124}Ce*, relative to ^{120}Cs, compared with experimental data [1]. The light product is also shown.

reaction we are interested in LPs only. Clearly, the $\ell = 0$ case shows that $2p$ and $3p$ are favorably preformed, and that ^{8}Be is preformed stronger than ^{6}Be, establishing the result of enhanced cross-sections for $2p$ and $3p$, together with ^{6}Be having a smaller cross-section compared to that for ^{8}Be.

Figure 3 shows our DCM calculated cross-sections for ^{124}Ce* at 150 MeV laboratory energy compared with the PACE4 predictions at the same level density paramater, and the experimental data [1], given relative to ^{120}Cs ($\equiv$ $3pn$ or ^{4}Li) (no error bars are given in the publication [1]). We notice that PACE4 calculations under-estimate the LPs and ^{6}Be data, but compare favorably for the remaining three (^{5}Li, ^{7}B and ^{10}C) IMFs (no predictions are given for ^{8}Be and ^{9}B), whereas, for the best fitted $2p$, $3p$, ^{5}Li and ^{6}Be cross-sections, the DCM predicts ^{8}Be ($\equiv{}^{116}$Xe) to be relatively more populated than ^{6}Be ($\equiv{}^{118}$Xe), similar to the case for the ground-state decay [8].

4. Summary and conclusions

The dynamical cluster-decay model (DCM) is used to calculate the relative decay cross-sections measured in ^{32}S+^{92}Mo→^{124}Ce* reaction at an incident $E_{\rm cm} = 111.29$ MeV ($\equiv E_{\rm Lab} = 150$ MeV). Neck-length ΔR is the only parameter of the model, whose value remains within ~ 2 fm, the range of validity of proximity potential used here. For the best fitted ΔRs of two LPs (2p and 3p) and two IMFs (^{5}Li and ^{6}Be), the relative population of ^{8}Be is found to dominate over ^{6}Be, possibly due to the α-nucleus structure of ^{8}Be [12]. Further experiments are required.

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